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Temperature Sensing Using Linear and Nonlinear Resistive Fluidic Components

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A fluidic temperature sensor using linear and nonlinear resistive elements has been designed and tested. The sensor output is independent of the geometries (if identical resistances are used), depending only on the fluid properties and the supply pressure. Theoretical calculations indicate that this sensor has a very good sensitivity throughout the temperature range between 20 and 1000 C and the preliminary test results are in good agreement with the theoretical predictions.

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FIGURES

1. INTRODUCTION

Temperature sensing using fluidic techniques has been investigated by many researchers. A common method is the use of edge tone fluidic oscillators[1,2] in which the temperature is sensed by relating the temperature to the frequency of oscillation due to changes in fluid properties such as the density and specific heat. Recently, Drzewiecki and Phillippi[3] used capillaries to sense temperature. They recognized the fact that the change of the pressure or flow in such a sensor is small. By using a laminar proportional amplifier gain block to amplify the signal, they were able to obtain useful signal output with their fluidic thermistor/amplifier circuits. However, the sensitivity (change in output to change in temperature) can drop over two orders of magnitude as the temperature rises from 20 to 1500 C. In order to retain the unique advantages of fluidic temperature measurement such as high reliability and ruggedness, a new scheme of temperature sensing is presented using passive fluidic elements with improved sensitivity throughout the temperature range.

This report deals only with the basic design concepts and the preliminary test results for the steady-state case.

2. DESIGN CONCEPTS

2.1 Flow through Capillary

The present design concept is based on the change of the fluid properties, such as the density and viscosity, with temperature. It is well known that the resistance, R, for fully developed flow in a capillary tube is dependent on the viscosity, μ, of the fluid such that

$$R = f(\mu) \tag{1}$$

Figure 1 shows a schematic diagram of a capillary tubing. From figure 1, for a fully developed flow, we can write the resistance, $R = \Delta P/Q$, as

---

[1] *C. R. Halbach, R. A. Otsap, and R. A. Thomas, A Pressure Insensitive Fluidic Temperature Sensor, Advances in Fluidics, ASME (1967).*

[2] *J. M. Kirshner, Survey of Sensors, Part II, Proceedings of the Harry Diamond Laboratories Fluidic State-of-the-Art Symposium, II (October 1974).*

[3] *T. M. Drzewiecki and R. M. Phillippi, Fluidic Thermistors or Fluidic Temperature Sensing with Capillaries, 76-WA/TM-1, ASME Winter Annual Meeting (5-10 December 1976).*

$$R = \frac{128\mu L}{\pi D^4} \tag{2}$$

or

$$\Delta P = \frac{128\mu LQ}{\pi D^4} \tag{3}$$

where

D = diameter (m)

L = length (m)

ΔP = pressure drop (kPa)

Q = flow rate (m^3/s)

μ = viscosity (kg/m-s).

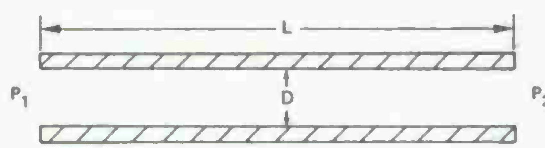

Figure 1. Schematic diagram of capillary tube.

Suppose that we have two capillary resistors in series and each resistor is at a different temperature as shown in figure 2. From figure 2, we have

$$P_o = \frac{P_s}{1 + \frac{R_1}{R_2}} , \tag{4}$$

where

P_o = output pressure (kPa)

P_s = supply pressure (kPa)

R_1, R_2 = resistance (kg/m^4-s).

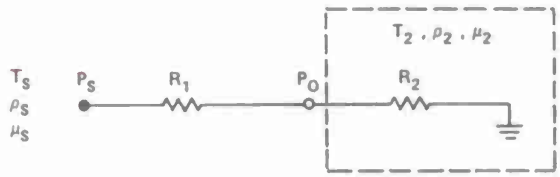

Figure 2. Schematic diagram of two capillary tubes in series.

Since

$$R_1 = \frac{128\mu_s L_1}{\pi D_1^4} , \quad R_2 = \frac{128\mu_2 L_2}{\pi D_2^4} , \tag{5}$$

equation (4) becomes

$$P_o = \frac{P_s}{1 + \dfrac{\mu_s L_1 D_2^4}{\mu_2 L_2 D_1^4}} . \tag{6}$$

For $L_1 = L_2$ and $D_1 = D_2$, equation (6) becomes

$$P_o = \frac{P_s}{1 + \dfrac{\mu_s}{\mu_2}} . \tag{7}$$

Equation (7) is the governing equation for the capillary temperature sensor.

2.2 Flow through Orifice

Figure 3 shows a schematic diagram of an orifice. For a flow through the orifice, we can write

$$\Delta P = \frac{\rho Q^2}{C^2 A^2} \tag{8}$$

or

$$R = \frac{\Delta P}{Q} = \frac{\rho Q}{C^2 A^2} , \tag{9}$$

where

A = area (m^2)

C = discharge coefficient

ρ = density (kg/m^3).

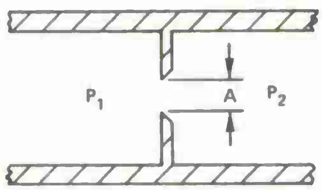

Figure 3. Schematic diagram of orifice.

Connecting the two orifices in series as shown in figure 4, we have

$$P_o = \frac{P_s}{1 + \frac{R_3}{R_4}} \tag{10}$$

or

$$P_o = \frac{P_s}{1 + \frac{\rho_s C_4^2 A_4^2}{\rho_4 C_3^2 A_3^2}} . \tag{11}$$

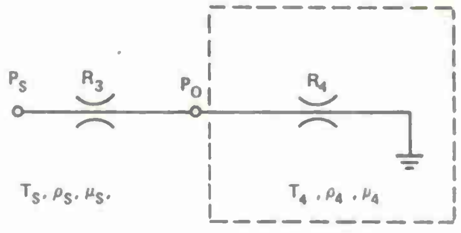

Figure 4. Schematic diagram of two orifices in series.

For $C_3 = C_4$ and $A_3 = A_4$, equation (11) becomes

$$P_o = \frac{P_s}{1 + \frac{\rho_s}{\rho_4}} \quad . \tag{12}$$

Equation (12) is the governing equation for the orifice temperature sensor.

2.3 Fluidic Passive Element Temperature Sensor

By connecting in parallel the capillary and orifice resistors (see fig. 5), described in previous sections, we obtained a temperature sensor with a high sensitivity over a large temperature range. From figure 5, we have

$$P_{01} = \frac{P_s}{1 + \frac{\mu_s}{\mu_2}} \quad . \tag{13}$$

and

$$P_{02} = \frac{P_s}{1 + \frac{\rho_s}{\rho_2}} \quad . \tag{14}$$

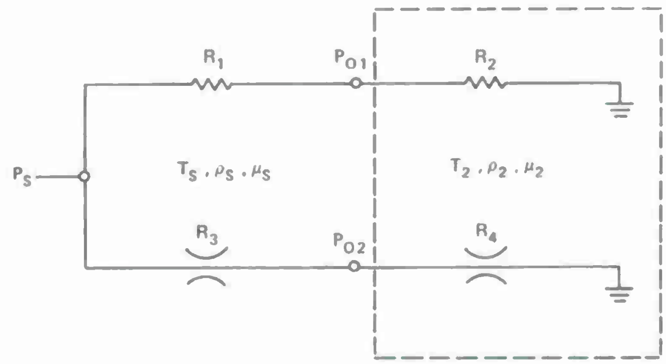

Figure 5. Schematic diagram of temperature sensor

Subtracting equation (14) from equation (13) we have

$$\Delta P_o = P_{01} - P_{02} = \left[\frac{1}{1 + \frac{\mu_s}{\mu_2}} - \frac{1}{1 + \frac{\rho_s}{\rho_2}} \right] P_s \quad . \tag{15}$$

Equation (15) is the governing equation for the temperature sensor. We see that the output pressure, ΔP_o, is directly related to the supply pressure, P_s. Therefore, we can consider P_s as the gain factor of the sensor. For gases, the first term on the right-hand side of equation (15) increases and the second term decreases as T_2 increases. Thus we have increased the sensitivity of this sensor over the linear resistor sensor.

3. THEORETICAL AND EXPERIMENTAL RESULTS

As indicated by equation (15), for identical resistors in each leg of the sensor, the sensor pressure output is independent of the geometries for the static case and depends only on the properties of the fluid and the supply pressure. Figure 6 shows two sample calculations of equation (15) using the following equation for the viscosity of air which is based on the data of Keenan and Kaye's gas tables[4]

$$\mu = 0.134 + 1.7678E\text{-}3T - 7.6433E\text{-}7T^2 + 1.8047E\text{-}10T^3 \qquad (16)$$

where

T = temperature (C)

μ = viscosity (10^{-6} kg/m-s)

and the equation of state for the density term in equation (15),

$$\rho = \frac{P}{R_g T} \qquad (17)$$

where

R_g = gas constant.

From figure 6, we can see that the calculated sensitivity of the sensor is very good over the entire temperature range and that we can change the sensitivity of the sensor by adjusting the supply pressure. Tests were conducted on a sensor that was composed of two 35.5-mm-long ceramic capillary resistors with 20 0.25-mm-diameter circular holes and two

[4] *J. H. Keenan and J. Kaye, Gas Tables, John Wiley and Sons, Inc., New York, NY (1965).*

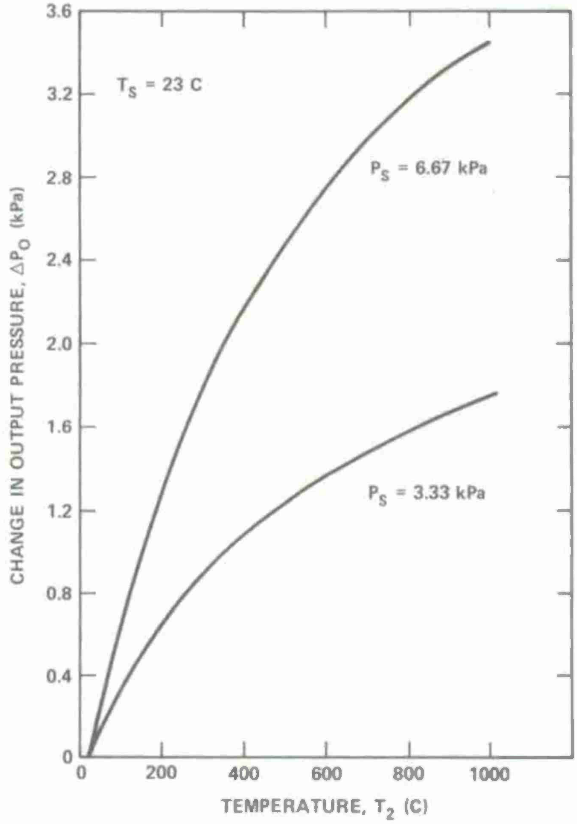

Figure 6. Sensor output versus T_2.

0.5-mm-diameter orifices. Figure 7 (p 12) shows test results of the pressure versus temperature compared with the theoretical calculations; they are in good agreement. This is especially true for the low supply pressure case. The reason for the excellent agreement for the low pressure case is that the fluid temperature and the environmental temperatures are very close to each other. For the high supply pressure case, it is reasoned that the actual fluid temperature was less than that of the environment. The accuracy of the sensor can be inproved at high supply pressure by placing an efficient heat exchanger in front of each sensing element. Otherwise, it is necessary to calibrate the sensor to account for the temperature difference.

4. SUMMARY

A fluidic sensor using linear and nonlinear resistors has been designed and tested. By using identical resistors in each leg of the sensor, the sensor output becomes independent of the geometries and dependent only on the fluid properties and the supply pressure. Theoretical calculations indicate that this sensor has a very good sensitivity throughout the entire temperature range of 20 to 1000 C. The test results and the theoretical predictions are in good agreement. The sensitivity of the sensor can be changed by adjusting the supply pressure to the sensor.

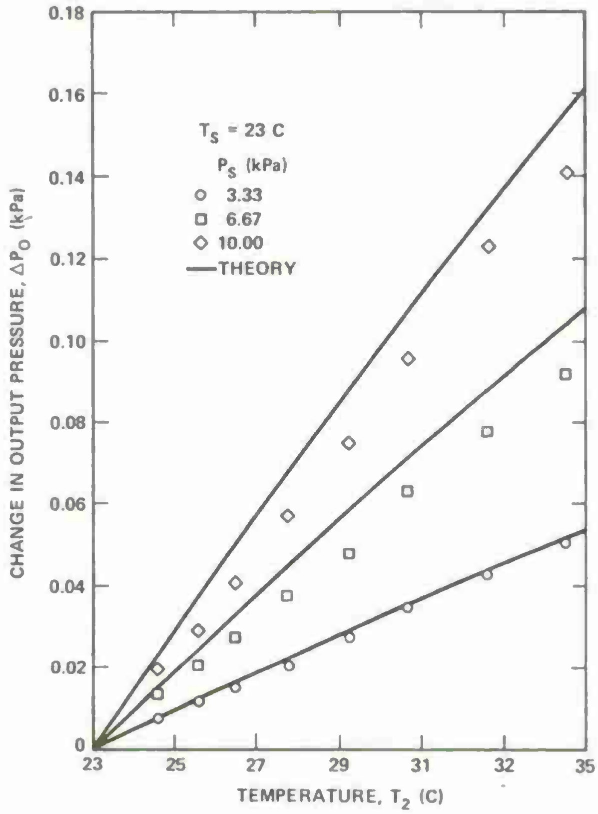

Figure 7. Comparison between test results and theoretical prediction of sensor outputs versus T_2.

NOMENCLATURE

A = area (m^2)

C = discharge coefficicent

D = diameter (m)

L = length (m)

P = pressure (kPa)

Q = flow rate (m^3/s)

R = resistance (kg/m^4-s)

R_g = gas constant (m^2/s^2-K)

T = temperature (C)

ρ = density (kg/m^3)

μ = viscosity (kg/m-s)

Subscripts

1,2...4 index

o output

s supply

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